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What is This?
Laryngeal Muscle Activity in Unilateral Vocal Fold Paralysis Patients Using Electromyography and Coronal Reconstructed Images

Tetsuji Sanuki, MD, PhD¹, Eiji Yumoto, MD, PhD¹, Kohei Nishimoto, MD, PhD¹, and Ryosei Minoda, MD, PhD¹

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Abstract
Objective. To assess laryngeal muscle activity in unilateral vocal fold paralysis (UVFP) patients using laryngeal electromyography (LEMG) and coronal images.

Study Design. Case series with chart review.

Setting. University hospital.

Subjects and Methods. Twenty-one patients diagnosed with UVFP of at least 6 months in duration with paralytic dysphonia, underwent LEMG, phonatory function tests, and coronal imaging. A 4-point scale was used to grade motor unit (MU) recruitment: absent = 4+, greatly decreased = 3+, moderately decreased = 2+, and mildly decreased = 1+. Maximum phonation time (MPT) and mean flow rate (MFR) were employed. Coronal images were assessed for differences in thickness and vertical position of the vocal folds during phonation and inhalation.

Results. MU recruitment in thyroarytenoid/lateral cricoarytenoid (TA/LCA) muscle complex results were 1+ for 4 patients, 2+ for 5, 3+ for 6, and 4+ for 6. MPT was positively correlated with MU recruitment. Thinning of the affected fold was evident during phonation in 19 of the 21 subjects. The affected fold was at an equal level with the healthy fold in all 9 subjects with MU recruitment of 1+ and 2+. Eleven of 12 subjects with MU recruitments of 3+ and 4+ showed the affected fold at a higher level than the healthy fold. There was a significant difference between MU recruitment and the vertical position of the affected fold.

Conclusions. Synkinetic reinnervation may occur in some cases with UVFP. MU recruitments of TA/LCA muscle complex in UVFP patients may be related to phonatory function and the vertical position of the affected fold.

Keywords
laryngeal electromyography, CT images, unilateral vocal fold paralysis, synkinesis

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Introduction

Neuronal control of laryngeal abduction and adduction is carefully orchestrated. The majority of motor fibers in the recurrent laryngeal nerve (RLN) provide adduction via the thyroarytenoid (TA) muscle, the lateral cricoarytenoid (LCA) muscle, and the interarytenoid (IA) muscle. The remaining 25% of motor fibers finely balance adductor motor activity to the posterior cricoarytenoid (PCA) muscle. Adductor and abductor axons as well as sensory and autonomic fibers are interwoven within the common trunk of the RLN.¹ When the laryngeal nerve is injured, regeneration occurs in each of these components to various degrees. The possibility for redirection of nerve fibers to inappropriate musculature exists in nerve trunks that supply multiple muscles.² This abnormal reinnervation is called synkinesis.³

The larynx rarely remains completely denervated or paralyzed in RLN injury. Laryngeal electromyography (LEMG) typically reveals evidence of muscle activity despite functional immobility.⁴,⁵ Axonal regrowth to the laryngeal musculature needs to be exact, or misdirection of regenerating fibers occurs. Multiple theories have been proposed as the mechanism of synkinesis including: scarring of the nerve nucleus, nuclear hyperexitability, and ephaptic transmissions, or multiple axonal sprouting.²,⁶

The leading theory involves aberrant axonal regeneration. After Wallerian degeneration, each axon opens endoneurial

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tubules as a new pathway to the laryngeal musculature. If axons enter the wrong tubules adductor fibers can grow and stimulate abductor muscles, resulting in uncoordinated movement or synkinesis. In animal models of experimental reinnervation the incidence of synkinesis varies between 66% and 88%. The incidence in humans is believed to be similar. Various degrees of synkinesis are more the rule than the exception in immobile larynges.

LEMG is useful in assessing the nature and extent of neurogenic pathology involving acute vocal fold paralysis. It can also aid in determining the prognosis in terms of recovery of RLN function. At the present, LEMG qualitatively establishes whether motor unit (MU) recruitment is normal or abnormal. Most LEMG studies in patients with vocal fold paralysis are performed to determine the likelihood of recovery of normal function. Several studies found recovery of electrical activity without vocal fold motion. The frequency of laryngeal synkinesis following RLN injury is unknown.

Videostroboscopy is the standard means of evaluating the vocal folds in patients with unilateral vocal fold paralysis (UVFP). This usually reveals the location of the affected fold, the process or absence of flaccidity, and the glottal gap during phonation. Overadduction of the ventricular fold, anterior-to-posterior shortening of the glottis, and anterior tilt of the artenoid portion may occur during phonation. Such supraglottal constriction prevents visualization of the vocal folds, and videostroboscopy cannot assess differences in the vertical position and thickness of the vocal folds.

The authors have developed a 3DCT technique using coronal reconstructed images to observe the thickness and location of the vocal folds during phonation and inhalation to determine glottal configuration.

This study assessed laryngeal muscle activity in patients with UVFP using LEMG, aerodynamic analysis and glottal configuration based on a 3DCT technique during phonation and inhalation.

Materials and Methods

Subjects
This study was approved by the Institutional Review Board of Kumamoto University Hospital. Sixty-one consecutive patients suffering from paralytic dysphonia, who had been diagnosed with UVFP at least 6 months previously, underwent LEMGs, aerodynamic analysis, and 3DCT before arytenoid adduction with or without nerve muscle pedicle implantation at the Kumamoto University Hospital between February 2002 and March 2011. Of the 61 patients, 40 were excluded from this study. Exclusion criteria were poor respiratory or swallowing function during the CT scanning, which would interfere with sustained phonation in the case of 6 patients, poor performance of phonation or inhalation task during CT scan in 7 patients, and poor performance of phonation task during LEMG in 25 patients. Two patients who had been affected by UVFP for less than 6 months were included because their RLN had been surgically resected due to primary disease. A total of 21 patients were included in this study, and Table 1 summarizes the subjects’ profiles. The causes of UVFP are listed in Table 2.

Laryngeal electromyography. Monopolar EMG tracings were obtained from all patients. The procedure required patients to lie in a supine position with the neck supported by a shoulder roll. A 4% lidocaine anesthetic was inhaled. An EMG measuring system (MEB-9200; Nihon Kohden, Tokyo, Japan) was used with filter settings between 20 Hz and 10 kHz. MU recruitment tracings were recorded with sweep speeds of 10 ms per division and a gain of 200 mV per division. A second channel utilized a microphone time-locked to the EMG signal. For these traces, the sweep speed was increased to 200 ms. Patients were awake and undated. Approximately 0.5 mL of 1% lidocaine with a 1:100,000 dilution of epinephrine was injected subcutaneously over the cricothyroid ligament. Monopolar fine-wire platinum electrodes were placed percutaneously through 23-gauge needles into both TA/LCA muscle complex with the neck extended. The hooked wires were consisted of a 0.65 mm platinum electrode with a polyamide coating that left only the distal 2 mm of the tip uninsulated. Wires had the tip bent backward to create a fishhook “barb” effect to hook the wire into the muscle as the insertion needle is withdrawn. The TA/LCA muscle complex is typically located at a depth of 2 cm, and the location was confirmed using video endoscope monitoring and a sustained vowel /i/ phonation. A 4-point scale was employed to

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values (mean ± SD)</th>
<th>Cause</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>13 males, 8 females</td>
<td>Postoperative Thyroid gland surgery</td>
<td>7</td>
</tr>
<tr>
<td>Age (years)</td>
<td>32-77 (59.5 ± 14.4)</td>
<td>Aortic aneurysm</td>
<td>5</td>
</tr>
<tr>
<td>Affected side</td>
<td>Left, 16; right, 5</td>
<td>Esophageal cancer</td>
<td>3</td>
</tr>
<tr>
<td>Period from onset to laryngeal electromyography (months)</td>
<td>3-366 (34.2 ± 78.8)</td>
<td>Mediastinal tumor</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lung cancer</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>Idiopathic</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lung tuberculosis</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brain infarction</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>21</td>
</tr>
</tbody>
</table>
grade MU recruitment where 4+ represented absent recruitment, 3+ greatly decreased recruitment, 2+ moderately decreased recruitment, and 1+ mildly decreased activity with a less than full interference pattern. Our methodology using the original scale of Munin et al for grading MU recruitment has been reported previously.9,13

Vocal function assessment. Vocal function assessment included maximum phonation time (MPT) and mean flow rate (MFR). To measure MPT, the patient was instructed to produce a sustained phonation of the vowel /a/ for as long as possible at a comfortable pitch and volume. MPT was measured twice for each patient using a stopwatch, and the higher value was recorded. MFR was measured using a phonatory function analyzer (PS-77E; Nagashima, Tokyo, Japan). The patient was instructed to produce the /a/ vowel at a comfortable pitch and volume while keeping their lips around the mouthpiece.

3DCT Scanning and Evaluation of Glottal Configuration

CT scanning was conducted for production of coronal multiplanar reconstructed images and 3D endoscopic images. Detailed methods are reported elsewhere.10-12,14 The subject lay in a supine position with a pillow under the neck. Scans were performed with a 64-row multislice helical CT scanner (LightSpeed VCT; GE Healthcare, Chalfont, St Giles, UK) at 200 mA, 120 kV, with a slice thickness of 0.625 mm and a table speed of 53.7 mm/s. Each subject was instructed to sustain the vowel sound /a/ at a low volume and inhale slowly for 5 s. Subjects practiced this maneuver prior to scanning. The subjects were scanned while sustaining phonation and during slow inhalation. Coronal images 1 or 2 mm thick were built perpendicular to the glottal axis. Before the evaluation, CT endoscopic images produced with the present method coincided well with those obtained through videostroboscopic images during phonation and inhalation.14,15

Two of the authors (TS, EY) evaluated the coronal images for each anonymous subject. Images were displayed on a monitor, and analyzed for differences in the thickness and vertical position of the vocal folds during phonation. To maintain consistency for the coronal images of all patients, measurements for the vocal folds were taken at the point before the anterior arytenoid cartilages. Images were also examined for differences in the thickness and horizontal position of the affected vocal fold between active phonation and subsequent inhalation. When differences between evaluations of a given subject were noted, both judges evaluated the images together until a consensus was reached.

Statistical Analysis

MU recruitment in LEMG and aerodynamic analysis was determined using the Spearman rank-correlation coefficient. Differences between LEMG findings, aerodynamic analysis, and coronal images were analyzed using the Mann–Whitney U test. Statistical analysis was performed using StatView 5.0 for Windows (SAS Institute, Cary, North Carolina). A P value less than .05 was considered to indicate statistical significance.

Results

Evaluation of Laryngeal Electromyography and Aerodynamic Analysis

MU recruitment was 1+ for 4 patients, 2+ for 5, 3+ for 6, and 4+ for 6. Nine of the 21 (42.9%) patients with UVFP had mildly or moderately decreased MU recruitment of TA/LCA muscle complex during phonation.

A comparison of LEMG findings and vocal function is shown in Table 3. MU recruitment grades in UVFP patients were negatively correlated with MPT (rs = –.51, P = .023). MU recruitment grades in UVFP patients were positively correlated with MFR (rs = .48, P = .0322).

Evaluation of Glottal Configuration Based on Coronal Images

The vocal fold on the affected side in 19 (90.5%) of the 21 subjects was thinner than the fold on the normal side during phonation. In 11 subjects (52.4%), the affected vocal fold was higher than the normal fold during phonation (Table 4).

Figure 1 shows the affected fold located at the same level as the healthy fold with identical thickness during phonation. The affected fold is directed medially, but not superomedially during phonation (Figure 1, thin arrow) and was directed superomedially during inhalation (Figure 1, thick arrow). Figure 2 shows the affected fold being thinner and located at a higher level than the healthy fold during phonation (Figure 2, thin arrow). The affected fold remained thin during inhalation (Figure 2, thick arrow) and was directed superomedially during phonation (Figure 2, thin arrow).

Figure 3 shows the affected fold being abducted during phonation and it is hardly recognizable in the coronal image. The affected fold was adducted and thick during inhalation (Figure 3, thin arrow).

All 9 subjects with MU recruitment of 1+ and 2+ had the affected fold located at an equal level to the healthy fold. Eleven of 12 subjects with MU recruitment of 3+ and 4+ had the affected fold located at a higher level than the healthy fold. There was a significant difference between MU recruitment and the vertical position of the affected fold during phonation (P = .0007).

Table 3. Vocal Function with MU Recruitment.

<table>
<thead>
<tr>
<th>MU Recruitment</th>
<th>MPT (s)</th>
<th>MFR (mL/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+ (n = 4)</td>
<td>4.95 ± 1.61</td>
<td>312.2 ± 156.7</td>
</tr>
<tr>
<td>2+ (n = 5)</td>
<td>5.82 ± 2.38</td>
<td>800.4 ± 566.4</td>
</tr>
<tr>
<td>3+ (n = 6)</td>
<td>3.78 ± 1.84</td>
<td>1066.6 ± 648.9</td>
</tr>
<tr>
<td>4+ (n = 6)</td>
<td>2.97 ± 1.23</td>
<td>791.8 ± 343.8</td>
</tr>
</tbody>
</table>

Abbreviations: MFR, mean flow rate; MPT, maximum phonation time; MU, motor unit.
We investigated the correlation between aerodynamic analysis and glottal configuration with coronal images. There were no significant differences between aerodynamic analysis and thickness of the affected vocal fold (Figure 4). For the vertical position of the vocal fold, MPT with equal positioning of the folds (5.24 s ± 2.0) was significantly greater than the vocal fold with a higher vertical position (3.36 s ± 1.6). There were no significant differences between the vertical position of the affected fold and MFR (Figure 5).

Discussion

Throughout the history of laryngology, investigators have investigated and theorized about the positioning of the vocal folds in cases of UVFP, the physiological basis for functional deficit and the fold position, and the likelihood of recovery. Since the work by Faaborg-Anderson in 1957 showing the normal electrophysiology of the larynx, many laryngologists have concentrated on diagnosis by LEMG. Hirano et al used LEMG to determine the prognosis in patients with vocal fold paralysis. The onset of electrical activity 6 months after the injury was a favorable indicator for recovery. They believed that after 6 months the presence of electrical activity was due to synkinetic activity. Hiroto et al also found electrical potentials in immobile folds, suggesting the presence of synkinesis.

In this study, the classification of Munin et al using MU recruitment was employed. They found that only MU recruitment was significantly related to vocal fold motion. In the present study, 9 of 21 (42.9%) patients had mildly or moderately decreased MU recruitment of TA/LCA muscle complex during phonation. Munin et al also assessed MU recruitment with LEMG in vocal fold paralysis. They showed that 5 of 22 patients had normal or moderately decreased MU recruitment of TA muscles. This indicates that synkinesis reinnervation of the RLN occurs in some cases of UVFP.

<table>
<thead>
<tr>
<th>MU Recruitment</th>
<th>Thickness of Vocal Fold</th>
<th>Vertical Position of Vocal Fold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thinner</td>
<td>Equal</td>
</tr>
<tr>
<td>1+ (n=4)</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>2+ (n=5)</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>3+ (n=6)</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>4+ (n=6)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>19</td>
<td>2</td>
</tr>
</tbody>
</table>

Abbreviations: MU, motor unit; TA/LCA, thyroarytenoid/lateral cricoarytenoid.
The Senmon and Wagner–Grossman hypotheses explained the fold position by selective abductor weakness, the IA muscle pull, or the cricothyroid (CT) muscle activity. Woodson\(^{18}\) reported on vocal fold position in 14 cases of UVFP (7 vagal and 7 RLN) and noted no differences between the vocal folds. She suggested that the fold position was related to a spontaneous reinnervation, not CT muscle activity as suggested by Wagner–Grossman. Woodson’s\(^{19}\) animal studies also demonstrated that variability in the vocal fold position was due to random reinnervation. Benninger et al\(^{20}\) described the position of the arytenoid cartilage as related to the relative balance of muscular contractions controlling arytenoid position. Blitzer et al\(^4\) determined that the patients who achieve good voice production with continued vocal fold immobility are different from patients with poor voice production and continued vocal fold immobility with LEMG. Seven patients in each group were studied, and all patients with a satisfactory voice were found to have synkinetic activity of the TA and PCA muscles. This suggests that the synkinetic reinnervation, rather than agonist-antagonist activity, while limiting mobility, provides good tone to muscle during phonation. Kokesh et al\(^{21}\) correlated the stroboscopic pattern with LEMG in patients with vocal fold paralysis. They found that 8 of 10 patients with LEMG evidence of reinnervation or partial denervation had symmetric mucosal waves, whereas only 3 of 10 patients with denervation had the same finding.

In the present study, TA/LCA muscle complex activity during phonation was related to the vertical position of the affected vocal fold with both coronal reconstructed images and aerodynamic analysis (MPT). The degree of reinnervation of the TA/LCA muscle complex associated with the affected vocal fold may be a determinant of the fold position. Limitations to the present study include the retrospective nature and the varying period from onset of UVFP to LEMG and CT scanning. Also MU recruitment measurement by LEMG was performed on only the TA/LCA muscle complex using monopolar electrodes. Candidates for arytenoid adduction with RLN innervation received LEMG as a preoperative examination. LEMG was performed not only for the TA/LCA muscles and CT muscles but also for the strap muscles involving a series of tasks.\(^{22}\) Hooked monopolar electrodes were suitable for this study given the range of patient motions over the course of testing.
Conclusions
Our data suggest that synkinetic reinnervation may occur in some cases of UVFP. MU recruitment of the TA/LCA muscle complex may be related to phonatory function and the vertical position of the affected vocal fold. Future studies should be conducted based on synkinesis testing using a concentric needle electrode to detect the presence of laryngeal synkinesis. In addition, conclusions would benefit from an increased sample size.

Author Contributions
Tetsuji Sanuki, design, data analysis, drafting and revising the manuscript, final approval of the version to be published; Eiji Yumoto, data analysis and final approval of the version to be published; Kohei Nishimoto, data acquisition of LEMG and coronal images and interpretation of data; Ryosei Minoda, contribution to make the manuscript and interpretation of data.

Disclosures
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